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An integrated approach towards identifying age-related mechanisms of slip initiated falls

Thurmon E. Lockhart *

Locomotion Research Laboratory, Grado Department of Industrial and Systems Engineering, School of Biomedical Engineering and Science, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

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Abstract

The causes of slip and fall accidents, both in terms of extrinsic and intrinsic factors and their associations are not yet fully understood. Successful intervention solutions for reducing slip and fall accidents require a more complete understanding of the mechanisms involved. Before effective fall prevention strategies can be put into practice, it is central to examine the chain of events in an accident, comprising the exposure to hazards, initiation of events and the final outcome leading to injury and disability. These events can be effectively identified and analyzed by applying epidemiological, psychophysical, biomechanical and tribological research principles and methodologies. In this manuscript, various methods available to examine fall accidents and their underlying mechanisms are presented to provide a comprehensive array of information to help pinpoint the needs and requirements of new interventions aimed at reducing the risk of falls among the growing elderly population.
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Keywords: Locomotion; Slips and falls; Slip initiated falls; Elderly; Accidents

1. Introduction

Reducing fall accidents has been a goal of many researchers for several decades. These researchers applied four primary approaches (epidemiology, biomechanics, tribology and psychophysics) to understand the causes of slip-induced fall accidents among the elderly. The epidemiological approach is concerned with the identification of the incidence, distribution, and potential risk factors for injuries due to falls in a population. Epidemiological findings clearly suggest that slip and fall accidents are one of the most serious problems facing the elderly population and constitute a major cause of mortality and reduced functioning. Tribology deals with surface dissipative processes in terms of the hydrodynamics and viscoelastic characteristics of contaminants and the shoe/floor interface. The tribological approach to fall prevention has concentrated on setting safe static and dynamic coefficient of friction (COF) limits for ambulation. Various slip-resistance measurement devices were proposed and developed to establish standards for floor slipperiness that are used by industries and building construction companies. Another approach to understanding the processes of slip and fall accidents has been to study it from a psychophysical perspective. Psychophysics is the relationship between the perception of a sensation and the physical stimulus which produces the sensation. In using the psychophysical methodology, researchers are obtaining further insight into the parameters of visual and tactile perceptions of the floor surfaces and their role in balance maintenance. Numerous investigators have documented the biomechanics of the shoe/floor interaction during walking and slipping in an effort to provide input to comprehensive control models. However, these models are strictly mechanical and do not take into account the response of people to different situations that the psychophysical approach provides insight into.

Many improvements in our understanding of slips and falls are attributed to the previously mentioned approaches.

* Tel.: +1 540 231 9088.
E-mail address: lockhart@vt.edu

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However, in spite of improvements in tribometric techniques to assess shoe/floor interactions, increased knowledge of the biomechanical responses to walking on slippery floor surfaces, and numerous studies in postural control, fall accidents continue to represent a significant burden to older adults both in terms of human suffering and economic losses. Although epidemiological studies clearly link the increased risk of falls with older adults, the mechanisms responsible for age-related fall accidents (both in terms of extrinsic and intrinsic factors and their associations) are not yet fully understood. In this article, several of our recent findings associated with age-related musculoskeletal and neuromuscular changes on biomechanical responses during slip-induced falls are reviewed to provide a better understanding of the mechanisms involved. In order to quantify age-related slip propensity and balance recovery mechanisms, a robust slip perturbation technique and methods for assessing slip severity were developed and implemented. Slip perturbation studies can provide knowledge concerning the initiating event to the final recovery events leading to falls and, thereby, identifying effective intervention solutions at various stages of the fall accident process. Furthermore, conventional biomechanical techniques (inverse dynamics and EMG analyses) were used in concert with slip severity measurements to answer the questions regarding the slip initiation and fall recovery mechanisms. It is hypothesized that successful interventions aimed at reducing age-related slip-induced falls require a more complete understanding of the mechanisms involved. Before effective fall prevention strategies can be put into practice, it is important to examine the chain of events in an accident in purview of the exposure to hazards, initiating events and the final outcome leading to injury and disability.

2. Approaches towards understanding fall accidents

2.1. Epidemiology of falls among the elderly

Fall accidents are among the most common and serious problems facing the elderly today. These accidents constitute a major cause of mortality, reduced functioning and premature nursing home placement (Robbins et al., 1989). In general, falls occur as a result of an interaction of various risk factors and situations which is modified by age, pathology, and environmental hazards (Fleming and Pendergast, 1993). This problem is further amplified by older adults' lack of responsiveness toward informing the physicians of their fall-related disorders and as a result, the problems remain undetected until preventable injury and disability occur (Cumming et al., 1990). Both the incidence of falls and the severity of the injuries resulting from fall accidents increase after middle age (Campbell et al., 1981). Accidents are the fifth leading cause of death in the older population (aged 65 and older), and falls make up the largest percentage of accidents (over 65%) for this age group (National Safety Council, 1998). More directly, 75% of deaths due to falls in the United States occur in 13% of the population aged 65 and over (Josephson et al., 1991). Approximately 35–40% of the elderly population living at home will fall annually, and about 1 in 40 of them will be hospitalized (Campbell et al., 1981; Exton-Smith, 1977). Of those admitted to the hospital after a fall, only about 50% will be alive one year later (Gryfe et al., 1977; Overstall, 1978). In those aged 75–80, falling becomes more prevalent as 35–50% will fall every year (National Center for Injury Prevention and Control, 2000). These figures are considered low estimates of the problem since most falls experienced by older adults are not reported (Josephson et al., 1991). Nevertheless, these falls rates from the United States of America (Tinetti et al., 1988) are comparable to those reported in other countries including the United Kingdom (Prudham and Evans, 1981), New Zealand (Campbell et al., 1981), and Australia (Dolinis et al., 1997; Kendig, 1996; Lord et al., 1993). Additionally, falls and hip fractures among older individuals rank as one of the most serious public health problems in the US, with costs expected to exceed $32 billion by the year 2020 (Englander et al., 1996). Furthermore, with the general increased life expectancy and the resulting increase in the proportion of elderly persons in the overall population (Administration on Aging, 2002), our society is likely to experience a greater number of slip and fall accidents, which may have an additional impact on the economy of the health care system.

Causes of falls among the elderly are many, and the classification of falls can lead to ambiguous descriptors due to the lack of consistency in the falls literature. In general, factors intrinsic to the elderly (e.g., sensory and musculoskeletal degradations), the types of activity engaged, and the hazards and demands of the environment contribute to most falls in varying extent (Fleming and Pendergast, 1993). Overall, about 55% of falls were related to medically diagnosed conditions (postural hypotension (Scott, 1976)), drop attack (Sheldon, 1963), and dizziness/vertigo (Lucht, 1971), and 37% were related to environmental hazards. More than 25% of fall related injuries in older adults result from slips and 66% of fall-related hip fractures occur on wet or slippery floor surfaces (Bulajic-Kopjar, 1999). Although age-related risk factors for falling have been mostly identified, clear identification of causes of fall accidents are still needed to target fall preventions among the elderly. For example, the rationale regarding home hazard modification techniques has been confirmed, however, the effectiveness in reducing the overall fall accident rate are not as clear. This may hamper our resource allocation to reducing fall accidents. Regional variations in accidental falls (rate) need to be identified. Variation of temperature and environment and accident rate needs to be further identified.

2.2. Surface tribology of human gait

The mechanics of walking is important in understanding slip-induced fall accidents as it determines the slip resistance characteristics of the shoe/floor interaction and initiation of a slip. During normal walking the forces applied by the foot act in three directions: vertical (F_v), horizontal (F_h) in the direction of walking, and transversal (F_t) to the direction of body motion (Perkins, 1978). At the time of heel contact, there is a forward thrust component of force (i.e., horizontal force) between the swing foot and the floor. This force (F_h) is affected by walking speed which is the product of cadence and step length. Forward horizontal force increases with increasing step length and cadence although the effects of cadence are more pronounced than the step length (Soames and Richardson, 1985). Longitudinal–transverse force (F_t) is the result of the lateral momentum produced by for example, an out-toeing walking pattern (Broer, 1966). The transversal force component (F_t) can be ignored in normal level walking due to the small transverse forces observed in locomotion experiments (Gronqvist et al., 1993). Vertical force (F_v) results as the body's center-of-mass (COM) and the downward momentum of the swing leg contacting the ground during the heel contact phase of the gait cycle. Vertical force (F_v) is affected by walking speed and cadence. These forces (i.e., ground reaction forces) must be opposed by an adequate frictional force on the floor surface to prevent slipping and tripping. As such, slip resistance characteristics of the underfoot surfaces are important for human locomotion and pedestrian safety. Slip resistance is defined as the frictional force opposing the movement of an object across a surface (American Society for Testing and Materials, 1975). This includes forces opposing movement in both static and dynamic phases of foot contact. The fundamental idea of slip resistance is that a slip will occur whenever the frictional force opposing the movement of an object is less than the shear force (F_h) of the contacting foot.

The force of friction can be viewed as the force developed between two contacting surfaces (acting parallel to the contacting surfaces) which resist any sliding of the materials. Previously, three laws were assumed to describe the force of friction when one solid body slides over another: (1) the friction force is proportional to the load – i.e., normal force, (2) the frictional force is independent of the area of contact, and (3) the friction force is independent of the sliding velocity. Leonardo da Vinci stated the first two laws, which were rediscovered in the 1690s by Amontons (1699). The third law was first expressed in 1785 by Coulomb (1785). Rabinowicz (1956) suggested that if the three laws were correct, then friction force will only depend on the applied load, and the coefficient of friction (COF) will be constant for any given pair of materials under all conditions. However, friction is not independent of sliding speed. The coefficient of friction between two materials may vary as much as 30–50% according to the velocity of motion (Rabinowicz, 1956). Already, in the early 19th century, it was established that the frictional properties of two bodies at rest (static) and in motion (kinetic or dynamic) differ, since the frictional force resisting the start of motion for two bodies at rest was greater than the resistance after the objects were in motion (Morin et al., 1835). By 1943, investigators realized that there must be a transition from static to kinetic friction (Sampson et al., 2004). Today, as a result of work by a number of investigators, the difference between the static versus the dynamic COF is undisputed. In most engineering applications, static COF is greater than dynamic COF. The static COF varies regularly as a function of the static application time (i.e., adhesion and deformation forces) and the dynamic COF drops off as the sliding velocity increases (e.g., hydrodynamics) (Bring, 1964; Caubet et al., 1964). Whether the static COF or the dynamic COF provides a better estimate of the degree of slipperiness is still undecided. In general, static COF is thought to express normal walking conditions during the heel contact phase of the gait cycle and dynamic COF is thought to be valid after the foot has started to slip (Strandberg and Lanshammar, 1981). The occurrence and severity of a slip may depend on frictional properties when slip starts as well as how the friction varies as a slip progresses (Lockhart et al., 2005). Thus, the differences between the static and dynamic COF of the shoe/floor interaction may be more important in terms of expressing slip resistance and reducing slip induced fall accidents (Gronqvist et al., 1993).

To protect people from slipping and falling, various groups have proposed that minimum values be set for the COF under standardized test conditions. In other words, by standardizing the shoe and floor conditions, applying a normal load, and measuring the resulting frictional force, the COF could be measured. In essence, these standardized COF values can be used to establish the slip hazard level for a given shoe or floor. However, the methods for determining the COF value for a particular shoe or floor material have not been standardized at present (Pfauth and Miller, 1976; Tisserand, 1985). Future integrated research is needed to understand the relationship between the floor surfaces, biomechanical and psychological factors, and characteristics of shoes to establish a safe COF to prevent slip induced falls.

In terms of the floor contamination, any fluid contaminant between two sliding surfaces will provide lubrication and thereby lower the dynamic COF values (Chaffin et al., 1992) and increase the slipping tendency. Acting as a modifier, the presence of contaminants will change both the slip resistant characteristics of a physical surface and the characteristics of the shoe/sole surface. In essence, the fluid will behave as a hydrodynamic squeeze film, and in this context, lubricating qualities are dependent on the following conditions (Chaffin et al., 1992; Proctor and Coleman, 1988). (1) Area of the contacting surfaces. The larger the area, the lower the dynamic COF values because the lubricant is not easily squeezed out. (2) Roughness of surfaces. The size, shape, and number of surface irregularities can allow the fluid to drain effectively, and hence improve dynamic COF values, compared to a smooth surface. (3) Velocity of the surface motions. Higher velocities will tend to trap fluids, but very slow velocities will allow time for fluids to drain. (4) Vertical loads. The greater the compressive forces acting on the fluid, the greater the amount of fluid squeezed from between the surfaces. (5) Fluid viscosity. The higher the viscosity, the longer the time required for the fluid to drain from between the surfaces. Further studies are needed to elaborate on the interaction of above five conditions during human locomotion to enhance our understanding of the role of friction in slip resistance, especially for the elderly gait. This information can be used to design effective slip resistant characteristics of shoe sole and floor combinations to reduce slip initiated fall accidents.

Surface geometry can also influence COF. Walking down a ramp/roof poses a significant slipping hazard due to the generation of higher shear forces when ambulating over an inclined surface than a level surface. Ground reaction forces have been investigated during descent of a ramp (Harper et al., 1967; Mcvay and Redfern, 1994). These investigations show that shear force increases as ramp angle is increased. Thus, the friction demand at the shoe/floor interface can increase with increases in ramp angle. For example, Mcvay and Redfern (1994) found that the mean of the peak friction demand across subjects increased from about 0.25 to 0.5 at heel contact as ramp angle is increased from 0° to 20°. In order to prevent slips and falls, walking on steep roof surfaces may require high slip-resistance characteristics for the shoe/floor interface, and exceeding a certain slope, slip-resistance required for walking may not be possible to achieve. Although, theoretical and experimental evidence provides support for the increased risk of slipping while ambulating on inclined support surfaces, the threshold level of the angle of inclination and effective shoe/floor interfaces for safe walking has not been scientifically determined.

2.3. Psychophysics

Psychophysical methods have been employed to investigate human judgment of slippery floor surfaces in an effort to provide an input to comprehensive viscoelastic/hydrodynamic models of the shoe/floor interaction (Chaffin et al., 1992). Psychophysics is the relationship between the perception of a sensation and the physical stimulus which produces the sensation (Gescheider, 1993). In using the psychophysical methodology, researchers have asked research participants to subjectively assess the slipperiness of the floor to obtain further insight into the parameters of vision and tactile sensation. Tisserand (1985) suggested that frictional values are estimated and memorized unconsciously from preceding steps (one's own model of slipperiness) and this information is updated whenever the subjects feels the floor conditions are different from what is expected (reality). Therefore, if there is a discrepancy between the model and reality (failure of the evaluation system) a slip and fall might result. To help avoid slip-induced falls, gait parameters are adjusted to correct for contaminated or slippery conditions. Persons who have a prior knowledge of a contaminated walkway adjust gait parameters by reducing friction demand, heel velocity and step length (Cham and Redfern, 2001). For a known slippery walking condition, young individuals adapted their gait within one step prior to stepping onto the slippery floor surface. In a recent study of elderly fall avoidance strategies, Lockhart et al. suggested that older individuals required an additional step to properly adjust gait for contaminated walking surfaces (Lockhart et al., 2002). These studies suggest that visual cues (e.g. color coding of floor surfaces) to enhance gait adjustment and recognition of changes in frictional properties are important and need to be addressed in future research.

2.4. Conclusion

In summary, improvements in our understanding of slip-induced fall accidents are directly attributed to the above approaches. Epidemiological studies suggest that fall accidents are a significant cause of deaths and disabilities among older adults and are the most serious public health problems facing the modern world. Furthermore, our society is likely to experience a greater risk of falls due to the general increased life expectancy and an increase in the proportion of elderly persons in the segment of overall population. In order to reduce societal and individual burdens from fall accidents, we must search for the mechanisms underlying these accidents in light of fall prevention. Effective fall prevention solutions require knowledge of the tribology as well as psychophysics. Together, these methods can help decouple the complex dynamics of age-related fall accidents and ultimately reduce future falls among the elderly.

3. An integrated approach towards identifying age-related mechanisms of slip initiated falls

A review of the literature on fall accidents indicated that multiple mechanisms are involved in age-related slips and falls. Numerous studies have identified various risk factors for falling. Factors intrinsic and extrinsic to the elderly, and the hazards and demands of the environment, contribute to most falls in varying extent. In general, the ability to walk safely and preserve balance in the event of a slip and fall is dependent upon intact sensory and musculoskeletal systems. However, with advancing age, a variety of physiological changes affecting these systems may interfere with gait and balance, placing these individuals at a higher risk for slip and fall accidents. In this section, samples of the methodologies and results from our previous slip perturbation studies are presented to demonstrate the experimental investigation of postural control, gait kinematic and kinetics, and biomechanical modeling of slip initiated falls utilizing a conceptual scenario of the injury process. The injury process associated with slip initiated falls includes four phases: (1) slip initiation, (2) slip detection, (3) fall recovery, and (4) contact event. Slip initiation describes the personal, environmental and biomechanical conditions that dictate whether a given walking step will result in secure foot placement or if the foot will accelerate away from the base of support. Slip detection and recovery describes the neuromuscular and kinematic control sequence wherein the individual attempts to arrest the fall utilizing sensory and motor mechanisms. Impact or fall occurs if the slip is initiated and recovery fails. Fig. 1 illustrates a hypothetical unexpected slip and fall situation with possible causes and effects. The process is divided into four distinct phases: environment, initiation, detection, and recovery. The environmental phase considers the effects of contamination. As indicated the presence of contamination (oil, water, etc.) will reduce the available static and dynamic COF of the floor surfaces (ADCOF – available dynamic COF example in Fig. 1). Consequently, a slip is initiated by the combination of low static and dynamic COF and higher friction demand. Here, initial gait characteristics such as slower transitional acceleration of the whole body COM and higher heel contact velocity may affect friction demand characteristics due to the alterations of foot shear force (Lockhart et al., 2003). Furthermore, there are certain processing stages that must be undertaken during the detection phase if a fall is to be avoided (recovery phase). During the detection phase, if a potential fall is imminent, sensory input must trigger or alert those centers responsible for response selection. One or more of the following sensory inputs may initiate this alerting process: proprioception, vision, and vestibular function. Age-related disruption of the quality of the signal from the periphery for effective balance control may delay the response selection and execution increasing the risk of slips and falls. Additionally, inability to generate the necessary counterbalancing joint moments (due to age-related musculoskeletal degradations) during recovery either in magnitude or in rate of development to control the body's horizontal and vertical momentum can increase risk of falls.

3.1. Slip initiation

The risk of slip initiation is directly related to the gait characteristics of the individual and the ground reaction force at the heel contact phase of the gait cycle (Lockhart et al., 2005). Initiation of a slip occurs when the frictional force (F_μ) opposing the movement of the foot is less than the horizontal shear force (F_h) during the heel contact phase of gait (Perkins, 1978). Specifically, at the time of heel contact, there is a forward thrust component of the foot against the floor resulting in a forward horizontal shear force (F_h). Additionally, a vertical force (F_v) occurs as body weight and the downward momentum load the contact foot against the ground. Frictional force is proportional to the vertical force, $F_\mu = \mu F_v$, with the constant of proportionality, μ, defined as the coefficient of friction. Hence, the coefficient of friction $\mu = F_\mu/F_v$ of the foot-ground interaction must be greater than the ratio F_h/F_v to avoid slip initiation. The significance of this ratio (F_h/F_v) is that it indicates where in the walking step a slip is most likely to occur (slip initiation). This ratio is also termed "required coefficient of friction (RCOF)" since it represents the general friction demand required to prevent the initiation of forward slipping (Redfern and Andres, 1984). In normal gait, there are five peaks of this ratio exerted between the shoe and the ground (Fig. 2). The first three peaks occur during the landing phase (i.e., heel contact) and the remaining two peaks occur during the take-off phase (i.e., push-off) of the gait cycle. Peaks 1 and 3 (note: sometimes a peak occurs after peak 3 – although implicated, some filtering will remove this peak, and therefore, most researchers use the peak 3 as the representative RCOF) are caused by a forward force, whereas peaks 2, 4, and 5 are caused by a backward force on the forceplate. Specifically, peak 1 is determined by the approach angle of the heel to the ground during forward walking. Due to the low vertical force applied to the ground during this initial gait phase, this peak has been found to be inconsistent in determining slip severity. Peak 2 can occur due to a backward force exerted on the heel shortly after the heel contact phase of the gait cycle. This force has been noted by several investigators, but extent of slip resistance and reasons for its existence is not clear. Peak 3 is caused by the backward reaction force that decelerates the motion of the body and the leg. During this time (70–120 ms), the vertical force has risen significantly and the proportion

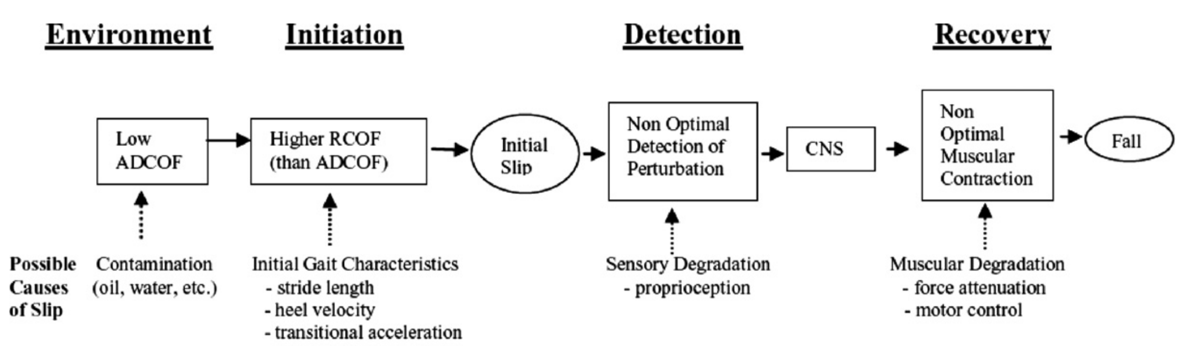

Fig. 1. The process of initiation, detection, and recovery of unexpected slips and falls with possible causes and effects due to aging (adapted from (Lockhart et al., 2005)).

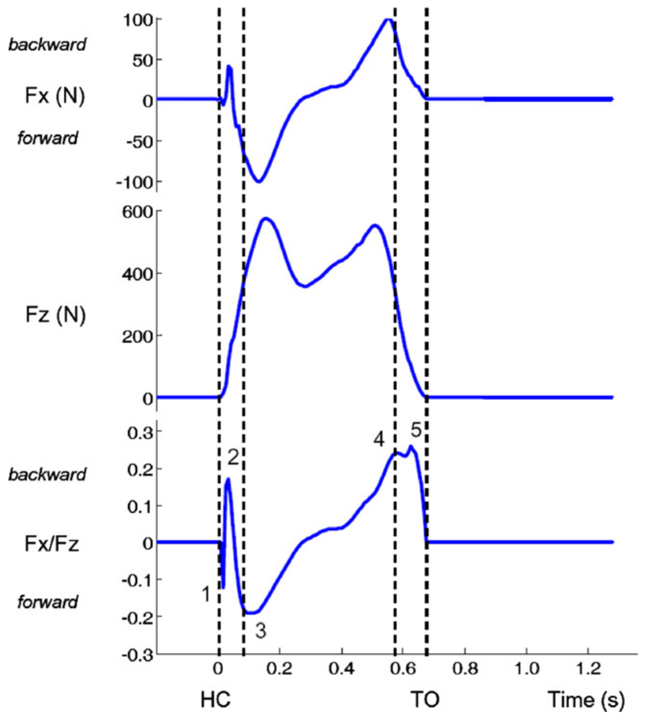

Fig. 2. In normal ground walking, typical horizontal (Fx) and vertical (Fz) ground reaction forces and required coefficient of friction (Fx/Fz) during one stance phase; HC and TO mark the instants of heel contact and toe off.

of the body mass is being applied directly to the contacting heel. As such, the error in the ratio (F_h/F_v) is relatively small. In progressing forward, more of the body mass is directed toward the contacting foot following the path of the whole body center-of-mass (COM) over the stationary foot, and the forward force causes the decrease in friction demand. During the push-off phase of the gait cycle, the ratio again increases due to the forces exerted by the foot propelling the body forward. As indicated earlier, the significance of the ratio is that it indicates where in the walking step a slip is most likely to occur. If the magnitude of F_h/F_v exceeds the coefficient of friction between the two contacting surfaces at a particular moment in time, a slip will result. In this view, there are two gait phases critical to slip initiation: (1) shortly after the heel contact where only the edge of the heel is in contact with ground (peak 3). Peaks 1 and 2 are not considered hazardous because F_v is quite small at peak 1, and F_h is directed backward at peak 2. (2) During the moment of the toe-off phase of the gait cycle when only the forepart of the shoe is in contact with the ground (peaks 4 and 5). Theoretically, forward slip at peaks 3 during the heel contact phase of the gait cycle is more hazardous since the forward momentum of the body is directed towards the slipping foot. Conversely, backward slip of the foot at peaks 4 and 5 is less hazardous since the whole body COM is transferred forward during the toe-off phase of the gait cycle. In essence, required coefficient of friction (i.e., F_h/F_v) at peak 3 can be used to identify slipping hazards or slip severity during normal level gait. Studies suggest that the number of slip and fall events increased as the difference between the RCOF and available dynamic COF of the floor surface increased (Hanson et al., 1999). Thus, changes in RCOF as a function of age-related gait adaptations can provide insight into risk of slip initiation among the elderly.

Walking patterns can influence friction demand characteristics. For example, the magnitude of shear force is directly coupled to walking speed, and an increase in walking velocity will increase the friction demand (Carlsoo, 1962; James, 1983; Myung et al., 1992; Soames and Richardson, 1985). Since the foot force vectors (extending from both legs) can be decomposed by taking the tangent of the angle between the leg and a line perpendicular to the floor, shear force increases with longer steps and, as a result, increasing the step length will, in general, increase RCOF (Gronqvist et al., 1989; Perkins, 1978). In this view, older adults' gait adaptations may not hinder safe walking, since older adults walk with shorter step length and slower velocity. In fact it should imply the opposite-shorter step length and slower walking velocity should have decreased the friction demand, and the likelihood of slip and fall accidents among the elderly should have been reduced. However, epidemiological studies clearly indicate that this is not the case. What gait characteristics then can influence age-related slip initiated falls? Investigating the gait parameters among the elderly, Winter (1990), Lockhart et al. (2003) reported that older adults' heel velocity was faster than their younger counterparts at or before the heel contact phase of the gait cycle. Increases in heel velocity during a critical time of weight bearing may increase the potential for slip-induced falls if the floor COF is significantly reduced (Lockhart et al., 2000). This is especially a concern for frail elderly individuals interacting with extremely slippery floor surfaces. Although implicated, a recent study suggests that for healthy older adults, heel contact velocity may not be the only factor modulating the friction demand and severity of slips and falls (Lockhart et al., 2005) (Fig. 3). A likely factor influencing the friction demand may be related to the forward momentum of the whole body COM shortly after heel contact. In normal level walking, COM of the whole body follows a path that describes a smooth sinusoidal curve on the plane of progression. Summits occur at the middle of the stance phase and during the double support phase of the gait cycle. Investigating the velocity profiles of the whole body COM during normal walking, Lockhart et al. suggested that the whole body COM velocity decreased prior to heel contact and increased shortly after the heel contact phase of the gait cycle (i.e., transitional acceleration of the whole body COM increases during this time period) (Lockhart et al., 2003). As such, momentum changes result in proportion to the inertial characteristics and path of the whole body COM altering horizontal as well as vertical foot forces and friction demand. In comparison to younger adults, older adults exhibited slower transitional acceleration of the whole body COM and influenced RCOF. The effects

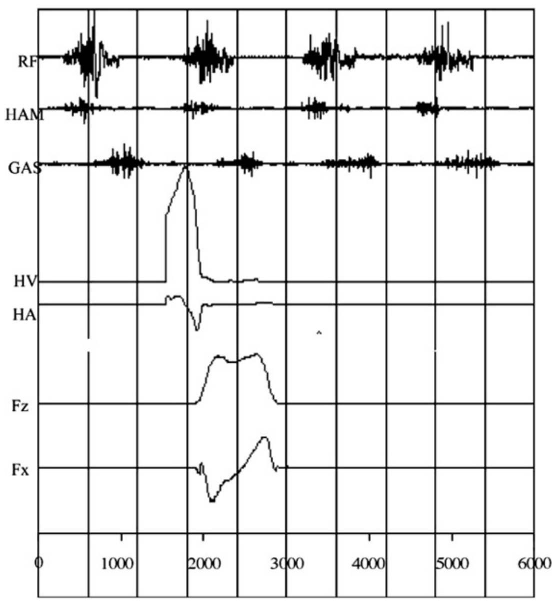

Fig. 3. Composite view of raw EMG of rectus femoris (RF), hamstring (HAM), and gastronemius (GAS) muscles, heel velocity (HV), heel acceleration (HA), vertical force (Fz), and horizontal force (Fx) during normal walking condition (1200 Hz). (Adapted from Lockhart and Kim, 2006).

of transitional acceleration may also play a role in reactive recovery to bring the body COM over the slipping foot to scale our motor responses and arrest a fall (Pai and Patton, 1997). A likely factor influencing the transitional acceleration of the whole body COM may be the ankle plantarflexors' biomechanical and physiological factors – i.e., plantarflexors produce more than half of the positive work during the push-off phase of the gait cycle (Winter, 1983). The push-off phase, which is observed between 40% and 60% of the gait cycle, is characterized at the ankle by a shortening (concentric contraction) of the plantarflexor muscles, resulting in power generation (Winter, 1991) (i.e., the whole body COM acceleration). Christ et al. (1992) reported the rate of decline in maximal voluntary isometric force between the ages of 25 and 74 years was largest in the plantarflexors compared with five other muscle groups. Coggan et al. (1992) reported 13–31% reduction in type IIa and IIb fibers and 25% lower mitochondrial enzyme activity in the gastrocnemius of older adults compared with young adults. Such a reduction in plantar flexor strength and endurance in the elderly may limit the maximal ankle joint moment and power generation (DeVita and Hortobagyi, 2000). Consequently, acceleration of the whole body COM (i.e., transitional velocity of the whole body COM) may be directly reduced and increase elderly adults' initial friction demand characteristics at the shoe floor interface of the contacting (swing) foot. Increased initial friction demand would lead to a higher likelihood of slips associated with low coefficient of friction floor surfaces (Hanson et al., 1999). In summary, age-related alterations of the ground reaction forces and gait kinematics may increase RCOF and the risk of slip initiation among the elderly. Further studies are needed to investigate the variation of heel contact velocity with engaged activities of the elderly (e.g., fatigue due to activities of daily living and its relationship to slip initiation). Further studies are also need to develop slip resistant shoes for the elderly in view of human gait characteristics.

The risk of slip initiation is also related to the feedforward mechanisms of gait adjustment prior to heel contact. Here, the psychophysical and biomechanical research approaches should be combined to provide further insight. Why psychophysics? Modification in muscle activity patterns when walking on different surfaces with varied friction give further proof that the person wearing the shoes can affect the outcome of exposure to slippery situations (Lockhart and Kim, 2006). Two key variables many prove to be important in relation to age-related slip initiation, that is, discriminative ability of our visual/tactile system to assess slippery floor surfaces and appropriate modulation of gait parameters. For example, we have conducted an experiment to provide a better understanding of how sensory changes in older adults affect discrimination of the floor slipperiness (Lockhart et al., 2002). Six college students and 24 older adults participated in this experiment. Four different floor materials were used in the experiment: ceramic tile, stainless steel, oily plywood, and oily vinyl tile. The dynamic coefficient of friction (DCOF) values for each surface were measured using a standard horizontal pull slipmeter with a rubber sole material and found to be: stainless steel −0.38, ceramic tile −0.29, oily plywood −0.16, and oily vinyl tile −0.11. Walking trials were conducted on a circular track using an overhead fall arresting rig. Posture and subjective assessments of floor slipperiness (using the rating scale) were obtained before and after walking over the contaminated floor surfaces. The results indicated that there was less agreement (before and after) among older adults in rating available DCOF of the floor surface than younger individuals (Fig. 4), and older adults slipped longer and fell more often than their younger counterparts. This suggests that visual cues (to enhance gait adjustment over a slippery floor surfaces) are important for reducing fall accidents and provide a basis for inferring that the recognition of changes in frictional properties is important in reducing slips and falls, especially among the elderly. Furthermore, it seems that learning took place while walking over the contaminated floor surfaces and as a result all participants, including the elderly, discriminated dangerous slippery situations more closely to the DCOF of floor surfaces. These results are in agreement with a previous study (Cohen and Cohen, 1994) indicating that tactile cues are more sensitive to physical measurements of dynamic COF and visual cues to slipperiness are inferior to tactile sensation. Thus, in unfamiliar conditions, people may rely on the primary but inferior visual information about a surface's traction until they actually walk on it. The potential for an accident can be created due to misjudgment of slipperiness based on initial visual sensing and the limited time available to make immediate

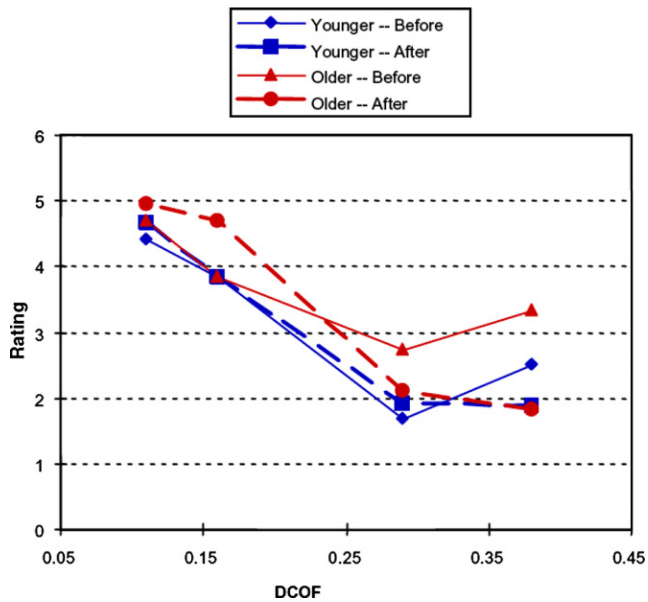

Fig. 4. Perceived slipperiness rating scores of young and old before and after walking on the floor surface.

adjustments in gait to accommodate for the hazardous condition. This may suggest that gait adjustment to slippery floor surfaces can be trained even for the elderly, given the awareness of tactile sensations. Further studies investigating the training effects of varied slip perturbations are needed to confirm this hypothesis.

An experiment was conducted to examine age-related differences in gait modifications during ambulation over a known slippery floor surface (Lockhart et al., 2007). The findings reinforced previous research by showing that both young and older age groups reduced step length, friction utilization, and heel contact velocity from normal gait to adjusted gait (the transitional step from a normal surface to a contaminated surface). Participants were able to reduce friction demand on the known slippery floor surface by adjusting both the stance leg and the swing leg muscle activities. For the stance leg and swing leg, longer hamstring activation duration was required to reduce step length, heel contact velocity and friction demand. During the step cycle, the calf muscle extensor group was mainly active during the toe-off phase and the quadriceps muscle extensor group was active following the toe-off phase to lift the leg, giving the foot sufficient ground clearance. Following this, the hamstring muscle group was active during the heel contact phase of the gait cycle (Lockhart and Kim, 2006). In summary, slip initiation is closely related to the perception of floor slipperiness and associated gait adjustments. This is especially important since our visual field and attention during locomotion is narrow (Imai et al., 2001) and divided in such a way that the first priority is given to objects falling within the effective visual field. Therefore, if a slippery condition is not detected within one's effective visual field (usually 10–15 feet ahead), the likelihood of fall accidents is significantly increased (Zohar, 1978). Once perceived, gait is adjusted accordingly. As such, discriminative ability of visual and tactile (e.g., proprioceptive system) sensory systems is important in veering away from slips during human locomotion and plays a vital role in modification of internal models using feedforward control mechanisms (Bard et al., 1995; Ghez and Sainburg, 1995).

3.2. Slip detection and recovery

Loss of balance was the most common cause of fall accidents among the elderly (Bulajic-Kopjar, 1999). Knowledge of the mechanisms involved in age-related balance loss is critical to effective fall prevention. Nashner (1983) suggested that at the time of potential balance loss, the central nervous system undertakes a triggering process to elicit a motor command/response to maintain dynamic equilibrium. During the detection of a slip perturbation, sensory input must trigger or alert those centers responsible for response selection (Lockhart et al., 2005). This alerting process may be initiated by one or more of the following sensory inputs: proprioception, vision, and vestibular function (Mirka and Black, 1990; Nashner, 1983). At the input stage, any disruption in the quality of the signal from the periphery may increase the likelihood of slips and falls. For the aging population this disruption can be amplified by sensory degradation. Numerous studies have documented the decline of postural control due to age-related sensory degradation. Vision plays a major role in maintaining stability, both in quiet stance and while undergoing movement such as walking (Tinetti et al., 1988). Visual acuity, accommodation, dark adaptation, peripheral vision, and contrast sensitivity, all of which are related to postural stability, may be affected by age-related changes and compromise balance control (Goldman, 1986; Kornzweig, 1977). For example, Pyykko et al. (1990) reported that older adults rely mostly on slower (latency 120–200 ms) visual control of balance than on vestibular and proprioceptive control. In contrast, the time available to achieve adequate frictional forces to avoid a dangerous slip and fall at the heel contact phase of the gait cycle is very short (100–110 ms). Thus, the potential for an accident can be created due to both the visual deficit and control strategy, as well as the limited time available to make immediate adjustments in posture to accommodate for a hazardous condition. Although implicated, visual control during dynamic slip recovery needs to be investigated to elucidate this possibility. Furthermore, the literature provides support that aging adversely affects proprioception (Skinner et al., 1986), movement co-ordination (Sparto et al., 1997), and muscle reaction times (Hakinen and Komi, 1986). As a result, age-related proprioceptive degradation may alter the use of feedback control mechanisms and may compromise balance control. The major contribution of the vestibular apparatus to posture is in maintaining balance of the body by perceiving the changes in direction as well as motion and stabilizing the eyes and head in space. Studies on the vestibular system indicate a marked decline in the vestibular apparatus among the elderly. As a result, older adults' vestibular system may hinder the optimum balance recovery response and may increase the likelihood of slips and falls (Kristinsdottir et al., 2000).

In order to investigate the effects of age-related sensory degradation on the outcome of slips and falls, an experiment was conducted to assess equilibrium scores utilizing computerized dynamic posturography (Lockhart et al., 2005). Similar to previous studies, significant equilibrium score differences were found across the age groups. The sensory organization test suggested that elderly individuals were less stable. Various postural sway models exist. Briefly, the equilibrium scores can also be modeled using the metastable potential to describe the cone of stability given the critical displacement amplitude beyond which the ankle or hip is unstable. This boundary limits (cone of stability) (McCollum and Leen, 1989) can be calculated given the critical forward or backward angle of stability and height of an individual (i.e., a typical forward lean angle assumed by the NeuroCom system is 6.25° forward and backward) (Lockhart et al., 2005). The relationship between sensory organization test scores and slip distances suggested that individual with lower scores (i.e., assuming instability due to sensory degradation) slipped longer (Fig. 5). More importantly, the relationship between equilibrium scores and motor control latency suggests that older adults were more likely to fall as a result of a delayed response selection process (Fig. 6).

After the response selection, the force generating capacity of lower extremity muscles and compensatory motor adaptations to attenuate lower extremity joint motions may play an important role in the fall recovery process. Furthermore, upper extremities as well as trunk and head movement modify the whole body COM transfer to fine tune the balance maintenance within the base of support (Liu et al., 2006). The recovery from balance loss depends largely on the strength of the lower extremity muscles

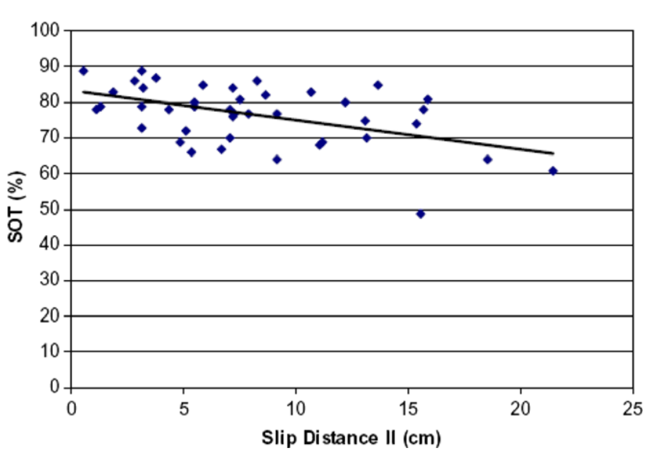

Fig. 5. Relationship between distance slipped and sensory organization scores of each participants ($r = -0.49$). In general, individuals with lower SOT scores slipped longer.

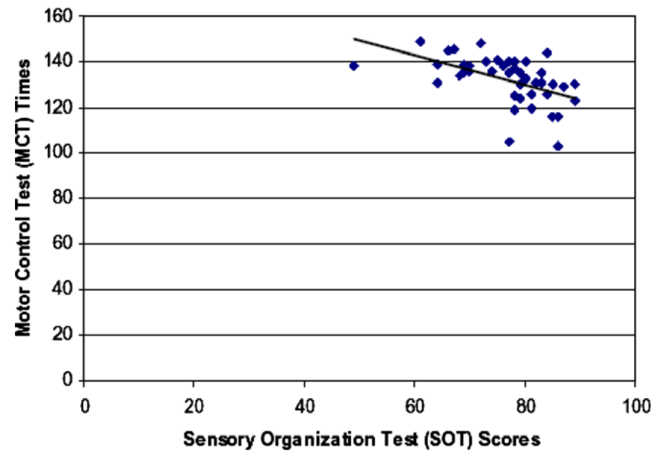

Fig. 6. The relationship between SOT scores and MCT times ($r = -0.51$). In general, individuals with higher SOT scores took less time to actively respond to the support surface movements.

which may be compromised with age. Additionally, capacity to generate fast large-scale motion (i.e., joint power) to constrain the momentum of a fall is critical to balance maintenance. In general, successful recovery from a slip event depends on substantial joint torque and power (Liu et al., 2006; Robinovitch et al., 2002).

Several studies have quantified the adverse effects of aging on hip, knee and ankle joint torque, which may contribute to older adults' increased fall frequencies. Evidence in support of this hypothesis comes from a number of investigations indicating a decline in voluntary muscle strength, rate of muscle force production, and increased likelihood of slips and falls. For example, Wolfson et al. (1995) and Larsson et al. (1979) reported that ankle and quadriceps muscle strength was significantly lower for those who fall as compared to non-fallers. Additionally, reduced lower extremity strength has been implicated as a factor contributing to the increased risk of falling (Whipple et al., 1987). Furthermore, aging may affect older adults' ability to generate explosive strength even more than their ability to generate maximum strengths (Thelen et al., 2000). Since recovery of balance upon a slip perturbation requires the development of moderate-to-substantial joint moments within a short period of time (i.e., joint powers), diminished rapid torque development capacities of older workers may require slightly longer muscular activation periods and larger activities to achieve the same mechanical effect as in the younger adults (Thelen et al., 2000). If this type of accommodation process exists, then older adults' loss of strength and execution speed may limit their available balance recovery strategies in the event of a slip and may increase the likelihood of fall accidents.

In order to improve our understanding of age-related balance recovery mechanisms after a sudden slip, a study was conducted to investigate the kinetic, kinematic, and EMG profiles of young and older adults. Subjects walked with a normal walking pace while wearing a safety harness. A slippery floor surface was introduced unexpectedly, and the recovery posture was collected. The available dynamic coefficient of friction of the floor surface was 0.06. Peak joint moment magnitude, generation speed and distribution ratio were quantified and analyzed. These parameters were assessed by using the inverse dynamics approach utilizing local segmental coordinates by way of the Gram-Schmidt orthogonalization process (Liu et al., 2006,). Furthermore, age-related initial response time of the perturbed and unperturbed foot and arm reactions to a slip perturbation were assessed (Lockhart and Liu, 2006).

Fig. 7 illustrates typical successful fall-recovery data starting from the heel contact point. The subject was a 29-year-old young male (height – 184 cm, weight – 87 kg). Normal gait events (e.g., heel contact and toe-off) were determined by the GRF, and slip events (slip start, slip peak, and slip-stop of the perturbed or slipping foot) were determined (Lockhart et al., 2003). Additionally, the trailing foot dynamics were assessed during the slip recovery process.

Initially on the perturbed side (perturbed foot) the heel does not slip forward. At this time, horizontal heel velocity decreases (Fig. 7a). This (no slip) is believed to be the result of the position of the whole body COM (closer to the other stance foot) (Mackinnon and Winter, 1993) during the heel contact phase of the gait cycle and may be influenced by tribological characteristics of the contaminant and floor interface. Shortly after heel contact (as the fore-foot comes down and the whole body COM shifts towards the sliding heel), the heel begins to slip forward (Fig. 7a). Afterwards, the sliding heel reaches maximum velocity. After this slipping period, the heel decelerates coming to a halt (i.e., slip-stop) (Lockhart et al., 2003). Lower extremity EMG activities and joint torque profiles of the perturbed leg suggest that slip-stop is achieved by first activating the hamstring muscles followed by the rectus femoris muscles and gastrocnemius muscles (Fig. 7e–g) to exert a flexor moment at the knee and plantarflexor moment at the ankle. On the unperturbed side (Fig. 7b), toe-off (unTO) occurs while the perturbed foot is slipping. This toe-off event of the unperturbed foot suggests that sensory system detection of a slip perturbation is not evident at this stage of the slipping process. Shortly after the unperturbed toe-off, the unperturbed foot is forced down quickly utilizing the hamstring and rectus femoris muscles (Fig. 7i and j) leading to complete double support (Fig. 7b – FootDown). Compared to the joint moment trajectories in the normal trials within the same length of time (about 500 ms after heel contact), ankle moment (Fig. 7c) was similar in shape and in magnitude. However, knee joint moment (Fig. 7d) was different in magnitude as well as the direction (extensor vs. flexor moment). Compared to the averaged EMG RMS during normal trials, EMG RMS in slip trials were remarkably more active in terms of magnitude (Fig. 7e–j).

Corresponding composite initial response times are illustrated in Fig. 8. For the perturbed foot (slipping foot), slip-stop (SlipStop) was defined as the instant when the forward heel velocity decreased to zero after SlipPeak

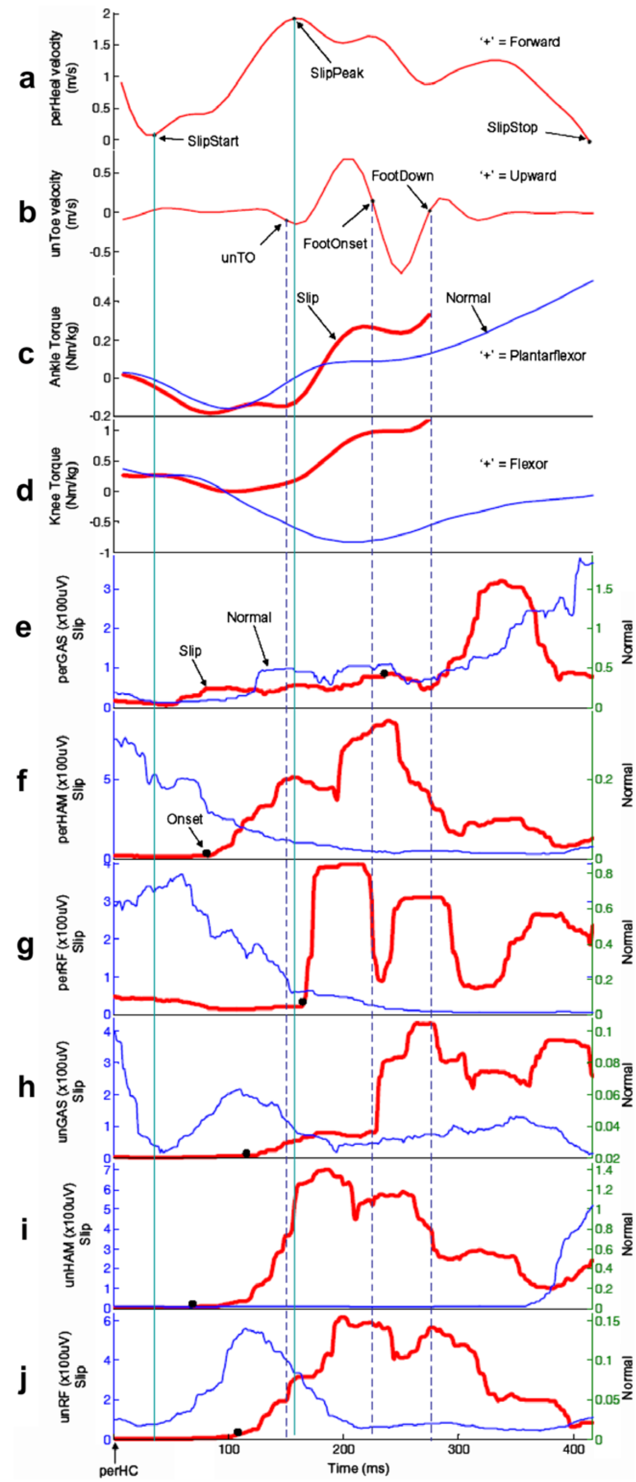

Fig. 7. Typical kinematics and muscle activation composite profile after slip initiation ((a) horizontal heel velocity on the perturbed side, with positive representing forward progression; (b) vertical toe velocity on the unperturbed side, with positive representing upward direction; (c) sagittal ankle joint moment, with positive being plantarflexor moment; (d) sagittal knee joint moment, with positive being flexor moment; (e–j) muscle EMG RMS on both perturbed and unperturbed side, with black circles marking the EMG onsets. In each graph, EMG RMS from slip trials were represented in bold curve with y axis on the left, and EMG RMS from normal trials were represented in thin curve with y axis on the right).

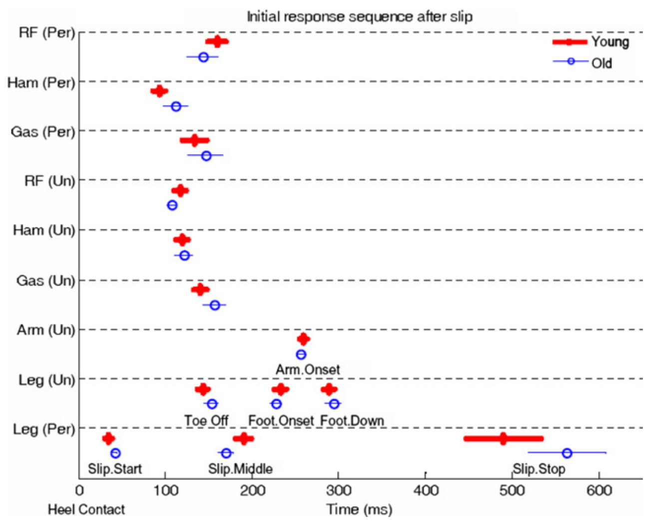

Fig. 8. Occurrence of critical events after slip start (Error bar represents SE; [a] unSide; unperturbed side/perSide: perturbed side).

(as defined by the peak sliding heel velocity). SlipStop was meant to provide additional descriptive timing information about heel dynamics during the slip. For the unperturbed trailing foot, foot reaction onset (FootOnset) was defined as the instant when the toe vertical position first went to a maximum after TO (toe-off). FootOnset was calculated to provide timing information about how fast the unperturbed foot responded to the slip perturbation. FootDown was defined as the instant when the toe vertical position went to its first minimum after FootOnset. FootDown was to provide timing information on when the unperturbed foot started to establish a wider base of support in order to assist an individual's reactive recovery process. The time period (FootReactTime) between FootOnset and FootDown was analyzed to reveal how fast the unperturbed foot could substantiate its role in the recovery process (by establishing a wider based of support) after a slip perturbation.

Each muscle activation onset time was determined in a way similar to previously published algorithms (Marigold et al., 2003). Briefly, the normal EMG activation ensemble average (meanEMG) and standard deviation (sdEMG) within one gait cycle was established from multiple normal gait trials. In slip trials, the occurrence of a reactive muscle response activity was defined as an increase in EMG RMS that exceeded meanEMG+2sdEMG or fell below meanEMG-2sdEMG for more than 30 ms. In total, 6 muscle onset variables (i.e., unGAS, perGAS, unHAM, perHAM, unRF, and perRF) from both the perturbed and unperturbed sides were determined.

The results indicated that younger individuals exhibited a faster slip start (Fig. 8). This may be due to the faster walking velocity of the younger adults. However, older adults reached mid-slip (i.e., peak sliding heel velocity) significantly faster than their younger counterparts. The differences of importance occurred during the mid-slip to slip-stop interval. In terms of the unperturbed foot, younger individuals' foot onset to foot down period was significantly faster than older adults. As a result, slip-stop occurred faster for the younger individuals than their older counterparts. Whether this effect is due to strength limitations or sensory degradation of elderly individuals needs to be examined further. Rapid and almost simultaneous muscle activation of the lower limbs after slip initiation was evident. Longer unperturbed foot reaction time (from onset to touch down) might be one of the determining factors of the high fall incidence rate for the elderly relative to their younger counterparts.

Several limitations apply to the slip perturbation experiments. A principal limitation in these studies arises from a situation of inadvertency. Unexpected slips and falls were induced utilizing the available methods described. However, as with all laboratory experiments, a tendency to anticipate "complete unexpectedness" will be limited by equipment and laboratory settings. In order to veer away from such anticipation, subjects were walking at a natural cadence for 15 min before being introduced to a slippery surface (same color and contrast as the base-line floor surface). As such, "unexpectedness" should be monitored during the trial via monitoring the subject's gait parameters prior to a slip perturbation event. Furthermore, subjects in these studies were aware of the fact that a slip and fall would be induced. This awareness of an impending fall may lead to pretension of lower extremity muscles, increased attention, or other heightened reactions that may not accurately reflect subjects' nervous and muscular responses in the event of unexpected losses of balance. Although implicated, a recent study (Pijnappels et al., 2006) suggested that anticipatory effects do not jeopardize the validity of perturbation experiments. A second limitation stems from the use of a safety harness used to protect subjects from falling. This may confound the biomechanical parameters. In order to eliminate analysis of these alterations, the collection of data should be limited to the time before fall-arresting usage by the subjects. Additionally, a drop of 25 cm before fall-arresting usage will ensure that the time of data collection portrays realistic slip and fall characteristics.

4. Conclusion

In summary, the initiation and recovery phases of slip and fall accidents may be affected by the intrinsic and extrinsic changes associated with aging and the environment. The methods outlined in this manuscript can provide experimental data and engineering-based analyses for the quantification of the slip propensity and balance recovery capabilities of older adults. Furthermore, by examining the biomechanics of postural perturbations such as a slip and the recovery strategies of both young and elderly individuals, we can seeks to quantify and identify the factors that influence the underlying causes of slip-induced fall accidents in the elderly. Quantification of biomechanical parameters associated with slip and fall accidents is a critical first step towards identifying the most significant factors influencing the outcome of slip-induced falls among the elderly. Precise knowledge of age-related musculoskeletal and neuromuscular deficits is crucial to the effective design of new intervention strategies aimed at reducing the risk of falls among the growing elderly population and to improve the target efficiency in allocating scarce healthcare resources to the most vulnerable individuals.

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Thurmon Lockhart is a human locomotion biomechanist and the Director of the Locomotion Research Laboratory at the Virginia Polytechnic Institute and State University where he is an Associate Professor of Industrial and Systems Engineering and the School of Biomedical Engineering and Science. He obtained his undergraduate and graduate degrees in Industrial Engineering from the Texas Tech University, and earned a Ph.D. in Biomechanics concentration from the same institution. His research focuses on understanding motor control aspects of slip induced fall accidents among workers and older population utilizing theoretical biomechanical modeling, human factors and ergonomics, postural control, gait mechanics, and point-of-care devices to develop and implement intervention strategies to reduce fall accidents.